Applying Options Analysis Techniques to Research and Development Projects

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Applying Options Analysis Techniques to Research and Development Projects: Developing a Conceptual Framework for NASA Aeronautical Investments[1]

Most studies of innovation and technology development in private sector firms commonly group the process into four constituent phases:[2]

- *Generation of an idea* involves synthesis of diverse information from both existing sources or from original research, including information about a market or other need and possible technology to meet that need.
- *Problem-solving* includes setting specific technical goals and designing alternative solutions to meet them.
- *Implementation* consists of the manufacturing engineering, tooling, and plant and market start-up required to bring an original solution or invention to its first use or market introduction.
- *Diffusion* takes place in the environment and depends on the rate of adoption of the innovation.

Building upon this basic approach, Rosenbloom developed a framework for the innovation process, depicted in Exhibit 1.[3] In this framework, technological change is viewed as a process within a structural context. Structural context may be divided into two categories. The organizational context includes, among other factors, the institution's goals, formal structure, leadership, and resources. The environmental context includes external technical and economic factors, including technological needs and constraints, government policies, competitive behavior, and industry trends.

Strategy formulation requires a perspective that cuts across the boundary of the organization , matching capability (organizational context) with opportunity (environmental context). Rosenbloom's framework has proven useful for examining a variety of private sector firms and for focusing on the role of the organizational level, but it needs to be altered to reflect differences between NASA and the companies in which Rosenbloom is interested.

Research and development activities at NASA differ in several important respects from the kinds of firms in which Rosenbloom was interested. First, NASA brings a very specific set of research skills and knowledge developed over years of the highest quality aerospace research and development. Second, while most private sector firms are looking for ways to improve their

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[2] James M. Utterback, "Innovation in Industry and Diffusion of Technology," *Science*, Vol. 183, (February 15, 1974), pp. 620-626.

[3] R.S. Rosenbloom, "Technological Innovation in Firms and Industries: An Assessment of the State of the Art," in P. Kelly and M. Kranzberb, eds., *Technological Innovation: A Critical Review of Current Knowledge,* San Francisco: San Francisco Press, 1978.

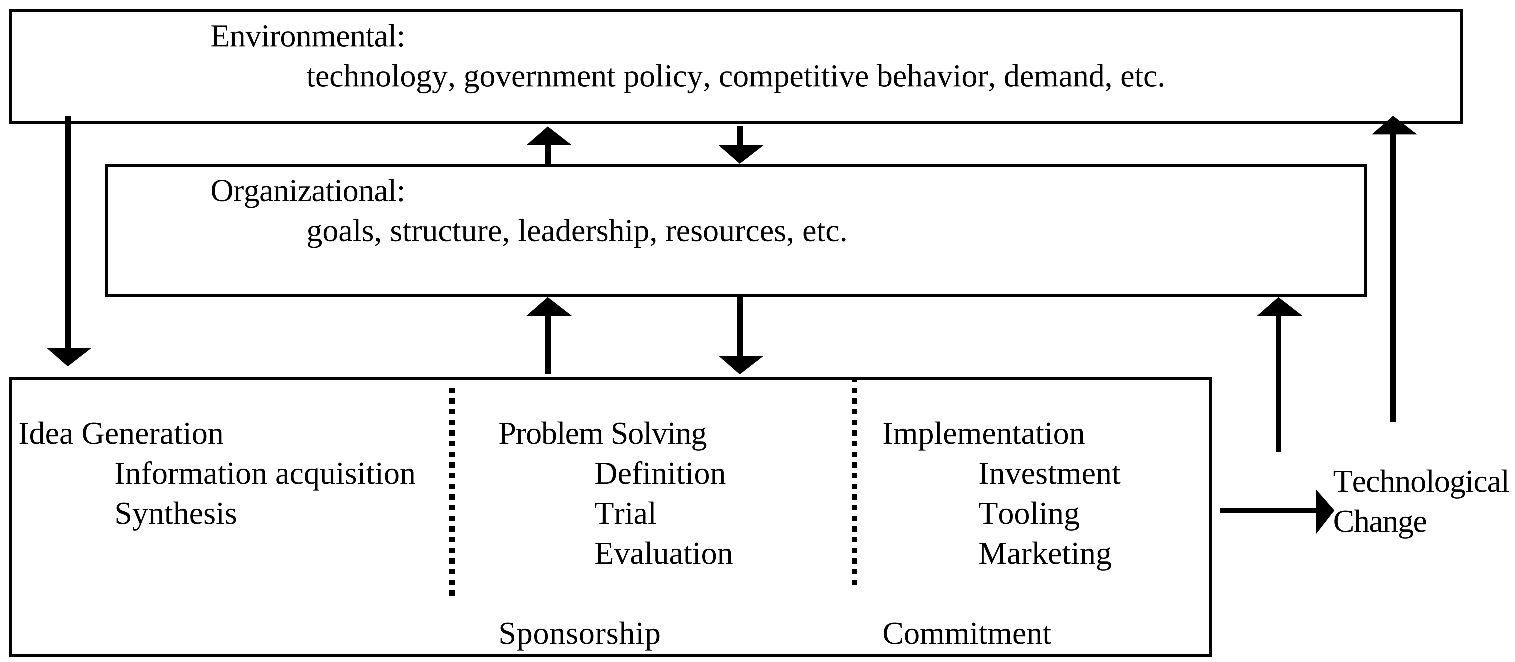

Exhibit 1: Rosenbloom's Framework

ability to compete in existing or closely related lines of business, NASA has a much wider potential array of areas in which its work could prove useful.

Rosenbloom also distinguishes between domains of use and domains of technology.[4] The technology mission of a Research and Development organization can be classified as product-targeted (one use/one technology), application-targeted (one use/ many technologies), technically-targeted (many uses/ one technology) or exploratory (many uses/many technologies). NASA's strengths and capabilities would seem to fit into the latter two categories rather than the former two. While it may be an advantage to have freedom about where to apply NASA's expertise, the disadvantage is that it may be far more difficult for NASA to assess the most pressing needs of its potential clients. Third, private sector firms are interested in taking their innovations or the results of their research and development activities all the way to implementation and incorporation into their normal production processes. NASA, on the other hand, will normally expect to turn over its research and development to a client. Thus, for NASA, there is also a question of how far NASA will continue development and at what point it will turn over the work to the client for final development and implementation.

Exhibit 2 contains a research and development strategy framework that may be better suited to NASA. It reflects the series of sequential decisions NASA faces in selecting the highest potential payoff areas for NASA aeronautical investments. The exhibit describes both the decision process and the context in which these decisions occur.

The process begins with basic research, by which we mean research into fundamental areas of science and engineering that are not directed at a specific problem or conducted with a specific application in mind. The decisions about the areas in which to undertake basic research are based in large part on NASA's technological comparative advantage. To some extent, the decisions might also be influenced by the external technological environment, but for the most part, NASA should focus on areas that take greatest advantage of its technological and scientific strength. More generally, an early critical step in business strategy is to identify the strengths and weaknesses of the business. In technology strategy, the corresponding step is in identifying distinctive technological competencies.

Once a basic research project is underway, periodic review points offer decision options. One alternative is that the project could be continued, that is, more resources could be provided and the research could continue. A second alternative is that the entire project or some aspect of it could be selected to move into the applied research phase. Clearly, these first two decisions are not mutually exclusive. A decision could be made to take part of the project to the applied research phase and continue basic research. A third alternative would be to terminate the basic research project. Here again, this decision is not mutually exclusive with a decision to take part of the project to the applied research phase.

[4]R.S.Rosenbloom, "Managing Technology for the Longer Term: A Managerial Perspective" in K.B. Clark, R.H. Hayes, and C. Lorenz, eds., *The Uneasy Alliance: Managing the Productivity-Technology Dilemma*. Boston: Harvard Business School Press, 1985.

The decision to move a project from basic research into applied research involves an assessment of the external technological environment. In this context, the term environment encompasses technology itself, societal values, government policy, market demand, and

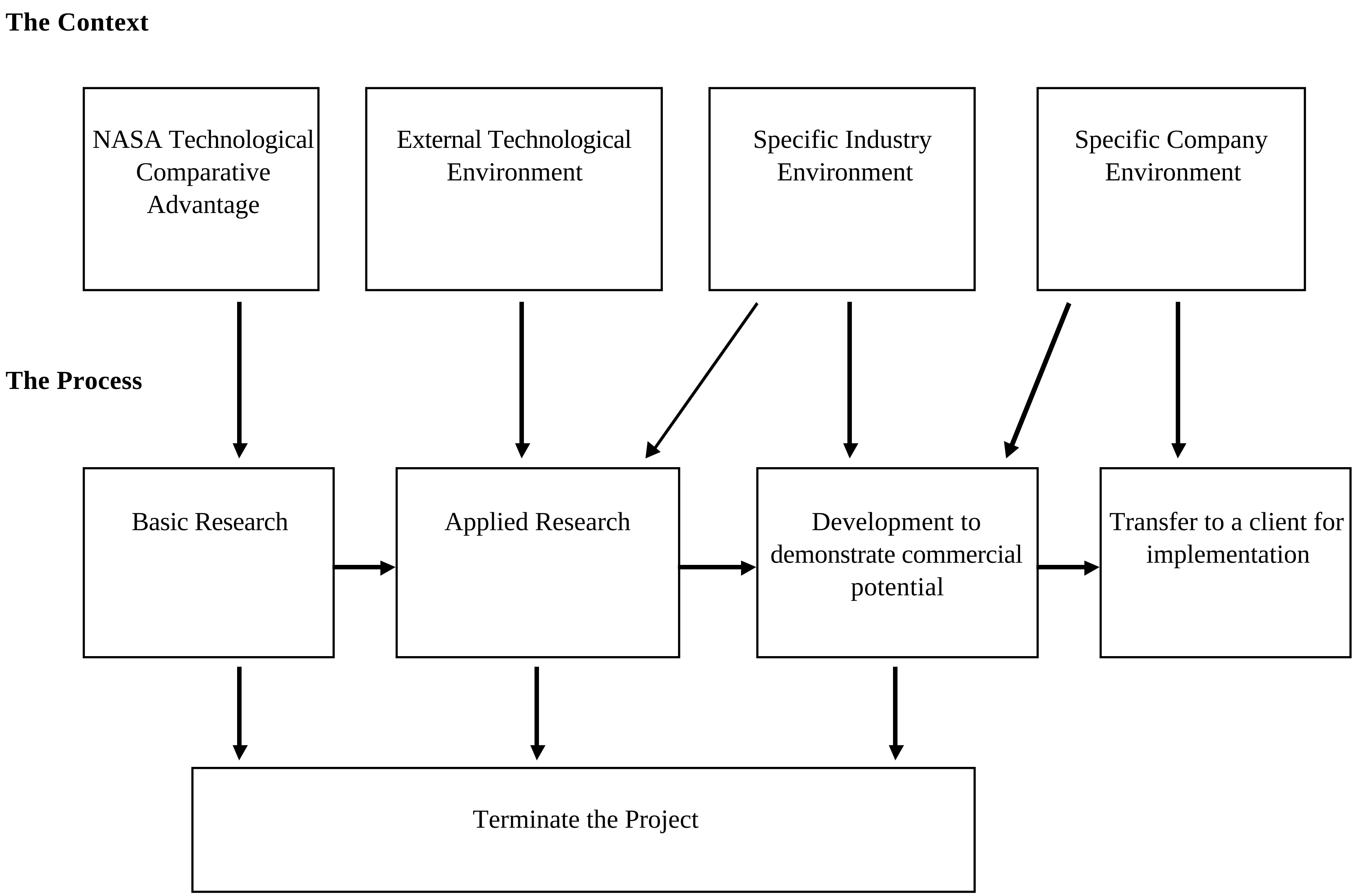

Exhibit 2: Research and Development Strategy Framework for NASA

competitive relations within key industries. NASA must match the potential technological innovation that could emerge with a perceived commercial need. That need must also be matched with the type of potential solution the applied research might provide. The challenge for NASA is to become aware of a wide range of commercial technological needs and to recognize when its basic research has yielded promising approaches to some of those needs. There are numerous examples of basic research that have yielded important applications in areas never envisioned by the researchers.

Once a project has entered the applied research phase, three decisions can be made. The first is to continue the project; the second is to move the project from applied research to the development phase where the goal is to demonstrate commercial potential; and the third is to terminate the project. During the applied research phase, the context of the external technological environment continues to play a role in shaping the research. At the same time, during the applied research phase, a potential application of the research has been identified and the context of the specific industry environment must begin to help shape the research.

If a project in the applied research phase demonstrates a technically attractive solution to a perceived industry need, it can be moved to the development phase. Here, the goals are to demonstrate that the technology can work in a production environment and that its cost and service characteristics show the potential for commercial success. During this phase, as in the previous ones, three decisions are possible at each review point. The project can be continued; the project can be transferred to a client; or the project can be terminated. During this phase, the context of the specific industry environment exerts an important influence and where a specific client has been identified, the context of a specific company environment may also become important.

Throughout these sequential steps from basic research to applied research to development and finally to transfer to a client for implementation, a progressively difficult decision is the choice between continuing a project and terminating it. A decision to terminate during the development phase may mean that considerable resources may have been devoted to the project in both that phase and in earlier phases. Inevitably, the question will arise whether the eventual decision to terminate could have been reached at an earlier phase at lower costs. Decisions to terminate are difficult, however, because many research projects encounter stages when they appear to hold little promise of success followed by breakthroughs. Giving up on a project too early can be as expensive a mistake as staying with a project too long.

In considering the external technological environment, the specific industry environment, and the specific company environment, NASA's strategic choices might be selected from three levels of activity:[5]

- A minimal form of strategy requires understanding the environmental pressures and trends relative to technologies, values, government, demand, and competition.

[5]Paul S. Adler, "Technology Strategy: A Guide to the Literature," in Richard S. Rosenbloom and Robert A. Burgelman, eds., *Research on Technological Innovation, Management, and Policy*, (Greenwich, CT: JAI Press, 1989).

- A higher level of strategic development would consist of a framework for deciding in which subregions of these environments NASA might optimally position itself.
- An even higher level of strategic development would acknowledge that the firm may have the possibility of shaping the environment and creating new opportunities: advancing the technology, influencing values and government policies, changing market demand, and altering the terms of competitive rivalry.

Within an industry, there may be an opportunity for technology to change the rules of the game.[6] From the standpoint of a firm, some innovations reinforce existing competencies whereas others can make existing competencies less valuable or even obsolete.

Concerning allocating funds to R&D activities, a number of interlinked budgeting decisions can be found: [7]

- What part of NASA's expected funding should be budgeted for expenditures over all functions in the succeeding years?
- How much of the total budget should be allocated to R&D activities?
- How should the R&D Budget be divided between different types of R&D activities, e.g. between research and development activities or between work on a new product and work on new processes?
- For a given research budget and a given development budget, which projects should be selected?

Often, these four budgeting decisions are handled at different organizational levels. Not surprisingly, decision models for the last three decisions often consider the funds to be allocated as fixed. A variety of techniques are available to help with these decisions, ranging from simple conceptual models[8] to more technical models utilizing multi-attribute utility theory and mathematical programming.[9]

To work within the context of a specific industry environment, NASA will have to be very familiar with the needs of a variety of aerospace industries. An assessment procedure for allocating R&D resources in private sector organizations may be of value in helping NASA better understand their potential clients.[10] An allocation system for R&D developed by Babcock and Wilcox attempts to identify the R&D technologies required to support the present and future business of the company. The first step of the process involves summarizing the business strategies of the operating divisions. Each unit's business plan is reviewed and the information supplied to R&D staff to help them assess "where we need to be and when". The next step is to

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[6] Gary Hamel and C.K. Prahalad, *Competing for the Future* (Boston: Harvard Business School Press, 1994), p. 54.
[7] Bertil Naslund and Bo Sellstedt, "An Evaluation of Some Methods for Determining the R&D Budget," *IEEE Transactions on Engineering Management,* Vol. EM21, No. 1, February 1974.
[8] Raymond Radosevich and Robert L. Hayes, "Toward the Implementation of R&D Resource Allocation Models," *IEEE Transactions on Engineering Management,* Vol. EM20, No. 1, February 1973.
[9] Gregory R. Madey and Burton V. Dean, "Strategic Planning for Investment in R&D Using Decision Analysis and Mathematical Programming," *IEEE Transactions on Engineering Management,* Vol. EM32, No. 2, May 1985.
[10] R.J. Dohrmann, "Matching Company R&D Expenditures to Technology Needs," *Research Management,* November 1978.

define technologies required to support the product line and business strategy. B&W then compares the current level of technology capability in the R&D Division relative to competitors. Such judgments are inherently subjective, but this process helps focus attention on areas where skills need to be improved and where competitive advantage might be extended.

This represents the basic approach to building a technology strategy. The next stage is to translate that R&D strategy into conceptual approaches to evaluate R&D projects. We will argue that traditional approaches to R&D evaluation fail to take into account their sequential character and their inherent managerial flexibility. This is particularly true for NASA aeronautical research activities, which not only have a variety of commercial applications, but also are likely to move through a sequential process of basic research to applied research to development of prototypes to commercialization efforts. This sequential character and the fact that each stage presents decisions for subsequent stages means that single time period investment models (such as discounted cash flow (Discounted Cash Flow) and net present value (NPV) fail to capture the actual behavior of managerial decisions through time. The net result of these traditional approaches is to undervalue such activity and to focus on R&D as an ordinary *investment* rather than as activities that create investment *opportunities*.

The Shortcomings of Traditional Investment Analysis

Investment in research and development activity traditionally has been considered under the classical subject of resource allocation or project appraisal under uncertainty. For private firms, corporate value creation and competitive position are critically determined by the proper evaluation of investment alternatives. For NASA, such considerations are analogous to the tasks of creating or extending new aerospace knowledge. Internally, the task is to strengthen and extend the research and development skills and resources of the organization, so that its long-term ability to generate, develop, and transfer technological innovations is enhanced.

The failure of traditional capital budgeting systems for research and development is quite broad. After World War II, capital budgeting and strategic planning emerged as two complementary but distinct systems for resource allocation. Capital budgeting developed into a decentralized process organized around individual or stand-alone projects based on discounted cash flow techniques -- principally, net present value in the private sector and benefit/cost analysis in the public sector. Unlike strategic planning, it focused on measurable cash flows, rather than on strategic benefits that may result from developing competitive advantage, and it sought to make appropriate adjustments for the timing and risk of these cash flows.

Because of these inherent limitations, Discounted Cash Flow techniques have not gained much acceptance in strategic planning, where competitive advantage and market leadership remained driving, dominant concepts. Even within strategic planning, the focus began to shift to how to best use existing resources within a given market structure, rather than how to create resources or to change a market structure. Discounted Cash Flow techniques were likely to be biased against capital investments with strategic and operating adaptability. As conventionally applied, such techniques were predicated on the assumption of passive management and allowed no flexibility to defer, abandon, expand, or otherwise alter a project.

Beginning in the mid-1980s, planning research began to focus on ways to link competitive advantage to the existence of internal organizational capabilities. Moreover, as businesses grew , they saw a greater need for decentralization of decision-making. Along with these new decentralized organizational structures (such as strategic business units) came decentralized resource allocation, which often favored a piecemeal approach. As a result, organizational capabilities and infrastructure often "fell through the cracks".

By the late 1980s, though, the failures of passive NPV analysis were becoming increasingly apparent. The failure of such methods to channel resources appropriately derives mainly from their inability to properly recognize the value of active management in adapting to changing information, market conditions, or to properly capture strategic value.

Nowhere was this more apparent than in research and development, a particularly important set of growth options. Many early investments can be seen as prerequisites or links in a chain or interrelated projects. The value of this early research may not derive so much from the expected directly measurable cash flows as from the future development options and opportunities they unlock (e.g., a new product or process, performance improvement, cost saving, or strengthening of core technology leadership). Despite a seemingly negative NPV, the infrastructure, experience, and potential by-products of the first-generation research may serve as a springboard for developing lower-cost or higher-performance future applications, or even for generating entirely new applications. But unless the organization makes the initial investment, subsequent generations or other applications will not even be feasible. The infrastructure and experience gained can place the organization at a competitive advantage, which may even reinforce itself if learning, cost, or efficiency curve effects are present. Such growth options are found in many industries -- especially in high technology, in R&D, in industries with multiple product generations or applications (such as aerospace and pharmaceuticals), in multinational operations, and in strategic acquisitions.

Investments in research and development are of fundamentally different character than other types of investments in at least three key ways. First, the return structures and potential of R&D investment may be quite different than, say, investment in capital equipment or a new production facility. These latter investments, while having uncertain returns, usually have outcomes that are normally distributed around some expected value. By contrast, R&D has a much different outcome distribution -- usually one with a small probability of a large success and a large probability of failure. This structure of outcomes means that traditional capital budgeting approaches that rely on expected values, such as net present value (NPV), fail to reflect the underlying opportunity of much R&D and generally result in decision criteria not to undertake projects. Moreover, extended approaches such as benefit/cost analysis may incorporate gains to society at large but still fail to incorporate the return structure of research and development activity.

Second, traditional capital budgeting approaches emphasize the evaluation of projects as of the current period (the essence of *net* present value). But by its very nature, most research activity involves stages; in effect each stage leads to an option to continue, expand, or abandon the next stage or level of activity. But traditional approaches fail to incorporate the value of this strategic flexibility, and in fact penalize it in expected-value weighting schemes (which in essence assume that the low probabilities of success will come to pass). These standard approaches have failed in this arena because they cannot properly capture managerial flexibility to adapt and revise later decisions in response to unexpected market developments or to research outcomes. They also cannot capture the strategic value resulting from proving a technology or capture the interdependencies between different research initiatives. Moreover, managerial decision-making flexibility is crucial to capitalizing successfully on favorable future investment opportunities and to limiting losses from adverse market developments or competitive moves.

Third, traditional project evaluation often ignores or downplays the strategic interaction between research efforts and the enhanced organizational capability. Such efforts may extend or strengthen core competencies and thereby strengthen the long term viability and performance of the organization. It is important to understand how companies obtain their investment opportunities in the first place. Sometimes investment opportunities result from patents, licenses, or in general the result of earlier investments. Generally, though, most investment opportunities flow from a company's managerial resources, technological knowledge, reputation, market position, and possible scale or experience, each of which was built up gradually over a sustained period of time. Such resources enable the company to undertake in a productive way investments that other companies or organizations cannot easily undertake. Corporate capabilities that enhance adaptability and strategic positioning provide the infrastructure for the creation, preservation, and exercise of real investment options.

Indeed, the value of most organizations lies not in their existing capital assets, but rather in their ability to invest and grow in the future. This is particularly true for companies in volatile and unpredictable industries, such as electronics, telecommunications, biotechnology, and technology-based sectors. Most of the economic and financial theories of investment have focused on how companies should exercise options already in place. But managers also need to understand how they can obtain investment opportunities in the first place,. This knowledge will help them develop better long-term strategies to determine how to focus and direct R&D, when to delay projects to determine future prospects of success, and when to accelerate development efforts to reduce uncertainty or to evaluate different alternatives.

At its core, research and development is about the creation, development, and extension of opportunities. Opportunities are options - rights, but not obligations - to take some action in the future. Capital investments in R&D, then, are essentially about options. Over the past two decades, and especially in the past few years, financial economists have applied option theories developed for financial instruments to decisions about investments that have non-normally distributed outcomes, that may present strategic opportunities, or that contain options to defer, expand, contract, abandon, switch, or otherwise alter activities or investments at various stages of a project's life.

The real-options revolution rose in part as a response to the dissatisfaction with traditional techniques of capital budgeting. Well before the development of real options models, corporate managers and strategists were grappling with the elements of managerial operating flexibility and strategic interactions. Dean (1951), Hayes and Abernathy (1980), and Hayes and Garvin (1982) recognized that standard NPV approaches often undervalued investment opportunities, leading to myopic decisions, underinvestment, and eventual loss of competitive position. Decision scientists further maintained that the problem lay in the application of the wrong valuation techniques, proposing instead the use of simulation and decision tree analysis to capture the flexibility of sequential investments over time, as in many R&D projects.

But decision analysis and simulation approaches also have central problems in how they handle or treat flexibility an the selection of appropriate discount rates to be applied to future events. While simulation can handle complex decision problems under uncertainty, the outcome is generally a risk profile of net present values, which does not have an intuitive decision criterion attached (the meaning of a probability distribution of NPVs is not clear when you know the underlying distribution are not normal). Even if management wants to base a decision on the probability distribution or risk profile of NPV, it still has no rule for translating that profile into an action. Furthermore, using the total variability of the NPV distribution violates the principle of value additivity so that projects might be promoted as a group, when each project alone might be unacceptable. But perhaps most importantly, Monte Carlo simulation is a forward-looking technique based on a predetermined operating strategy offering roughly symmetric outcomes. It cannot handle well the asymmetries in the distributions introduced by management's flexibility to review its previous decisions as uncertainty is resolved over time. Management, in reality, can adapt to surprises in ways that simulation models cannot.

Similarly, decision tree analysis (DTA) also has its problems. Decision analysis helps management structure problems by mapping out alternative managerial actions contingent upon possible states of nature. It is particularly useful for analyzing complex sequential investment decisions when uncertainty is resolved at distinct, discrete points in time. Decision analysis forces recognition of interdependencies between the initial decision and subsequent ones.

Decision analysis techniques work by creating a "tree" of contingent outcomes; once this array has been established, probabilities are assigned to each "path" and then the overall decision structure is evaluated by "averaging out and folding back" the tree based on calculations of the outcomes and their associated probabilities. In practice, this means management should choose the alternative that is consistent with maximization of expected utility. In capital budgeting, this criterion involves the decision that maximizes the risk-adjusted expected NPV.

While decision analysis is good at laying out and evaluating contingencies, it assumes that the entire project must be "played out". In practice, management may not actually have to be committed to a project for its entire ex ante expected life. Management may have the opportunity to abandon or transform the project. Management does not have to commit to a path of decisions at time zero, as is assumed with decision analysis. The asymmetry introduced by this flexibility provides management with downside protection consisting of the option to choose the maximum of the expected value from continuing or the value of abandoning the project. In principle, this flexibility to abandon can be built into decision analysis, but they are still based on probabilistic estimates quantified at the time of the initial decision.

Decision analysis also has other practical problems. First, decision analysis can become "decision-bush analysis" as the number of different paths expands geometrically with the number of decisions, outcome variables, or states considered for each variable. But the most serious problem is how to determine the appropriate discount rate. Decision analysis generally uses a constant discount rate that presumes that uncertainty is resolved continuously at a constant rate over time, not at discrete periods. But in multi-stage projects, the risk profile may be changing over time, as uncertainty is resolved. Thus, what is needed is a way to incorporate the decision analysis approach with better treatment of flexibility and discount rate dynamics.

Conventional Discounted Cash Flow/NPV approaches that either ignore real options and strategic considerations altogether or attempt to value real investment opportunities with asymmetrical claims by using a constant risk adjusted discount rate can lead to significant errors in valuation, since asymmetric claims on an asset do not generally have the same discount rate as the asset itself (in general, flexibility means that future investment decision may be less risky than if they are required to be taken now). Option valuation can be seen as a special version of decision tree analysis that is better suited to valuing sequential, interdependent investments.

Foundations and Building Blocks

Options theory was developed by Black and Scholes in their now famous 1973 paper. While our work here is not intended to provide a full explication of options theory; for that, the reader may find a more complete discussion in any high quality graduate-level corporate finance text, such as Brealey and Myers (1991) or Ross, Westerfield, and Jaffe (1993). In the interest of clarity, though, we will review the basic points here.

An option is defined as the right, without an associated symmetric obligation, to buy (if a call option) or to sell (if a put option) a specified asset (usually a share of common stock) by paying a prespecified price (known as the exercise price or the strike price) on or before a prespecified date (known as the expiration or maturity date). If the option can be exercised before maturity, it is known as an American option; if it can be exercised only at maturity, it is known as a European option.[11] The key aspect is that value derives from the option-holder's opportunity to exercise the option only if it is in the holder's best interest to do so. This flexibility and sequential determination of value is also characteristic of many R&D projects s we will see later in this paper.

Under a set of particular assumptions concerning the behavior of asset values, Black and Scholes show that a call option on a share of stock can be valued as:

$$C(S,t,E) = [SN(d_1) - Ee^{-rt}N(d_2)] / \ (\sigma\sqrt{t})$$

where :

[11] As we will see later, most R&D projects are European call options in character.

$$d_1 = [\ln(S/E) + (r + \tfrac{1}{2}\sigma^2)t] / \sigma\sqrt{t}$$

and

$$d_2 = d_1 - \sigma\sqrt{t}$$

and where the terms are defined in the previous paragraph and using the following symbolic notation:

C = value of call option
S = value of the underlying stock
E = exercise price of the option
t = time till expiration
e = 2.71828
r = risk-free rate of interest
σ = the standard deviation of the stock returns
N(.) = the cumulative standard normal distribution function

Although at first glance the formula appears complicated, the Black-Scholes model incorporates many of the aspects of options that are intuitive to managers. For example, other factors being held constant, the value of a call option is higher (1) the higher the value of the underlying asset (here, the stock price); (2) the longer the time till expiration (since more uncertainty can be resolved); the lower the exercise price (the less it costs you to take advantage of the subsequent opportunity); the higher the variance of asset returns (since the more variable the possible outcomes, the more valuable the option to abandon or to invest at a future date as uncertainty is resolved); and finally, the higher the risk-free rate (since the exercise price is not paid until the future and the higher the discount rate the less burdensome this is in present value terms). In sum, the call option is more valuable the higher the gain to be received (S) and the lower the cost (E). The greater the time till expiration and the greater the volatility, the more valuable since it gives the holder the right to benefit from higher upside movements while being subject only to a maximum loss of the initial investment (call premium) if things do not turn out well.

To obtain Black-Scholes options values in practice, one may use short-cut tabulated values given in any finance text; one is provided in the appendix to this paper for convenience. First, calculate $\sigma\sqrt{t}$ (the standard deviation times the square root of time till expiration) to specify the appropriate column; then calculate $S/(Ee^{-rt})$ (the asset value divided by the present value of the exercise price) to identify the proper row. The table entry at the intersection of the correct row and column gives the value of the option relative to the underlying asset value, so we need to multiply the table entry by the asset value to obtain the option value. Thus, suppose we take an example of an R&D project that has a 4 year initial stage[12]; a standard deviation of possible outcomes of 40% (.40); an initial asset value (investment) of $50; an exercise price of $100 (for example, to commercialize the results if successful); and a risk-free rate of 10 percent. This leads to a column heading of $\sigma\sqrt{t}$ = .40*2 = .80 and a row value of $S/(Ee^{-rt})$ = 50 / (100*$e^{-.40}$) = .75. This leads to a table entry at the intersection of this column and row of .2178. This can be interpreted as saying that the option has a value equal to 21.78% of the asset value, or $10.89. Thus, option tables can given us the value of options both in percentage and in dollar terms, if we can specify a few key aspects of an R&D project. Since such factors are inherently difficult to know, in practice, estimates are made of different possible values and the resulting range of option values then calculated. This is somewhat like the financial analogue to the technical assessment of the project quite common in R&D reviews.

[12]This example is taken from L. Trigeorgis, *Real Options: Valuing Managerial Flexibility and Strategy in Resource Allocation*, (Cambridge: MIT Press, forthcoming 1996).

Adapting Options Theory to Real Options

Options, whether analyzed under Black-Scholes, Cox binomial, or Merton arbitrage approaches[13], are valued on the basis of a no-arbitrage equilibrium, using portfolios of traded securities to replicate the payoff to options. In other words, we construct option combinations that are riskless, and then price these combinations using risk-free interest rates (typically, Treasury securities). The actual valuation of options in practice has been greatly facilitated by Cox and Ross's (1976) recognition that an option can be replicated (or a "synthetic option" created from an equivalent portfolio of traded securities). Being independent of risk attitudes and of considerations of capital market equilibrium, such risk-neutral valuation enables present-value discounting, at the risk-free interest rate, of expected future payoffs (with actual probabilities replaced by risk-neutral ones), a fundamental characteristic of "arbitrage-free" price systems involving traded securities.

Can we use this approach to value real options, applying the theory to capital budgeting where projects are not traded in active markets? Mason and Merton (1985) and Kasanen and Trigeorgis (1994) show that real options may in principle be valued similar to financial options, even though they may not be traded, since in capital budgeting we are interested in determining the value of the project as if it was traded in a market (that is, their contribution to the market value of a publicly traded firm). The existence of a traded "twin security" that has the same risk characteristics as the nontraded real asset is sufficient for real option valuation.

This is the same conceptual assumption used by standard discounted cash flow approaches, including NPV. These Discounted Cash Flow methods attempt to determine what an asset or project would be worth if it were to be traded. Recall that in typical Discounted Cash Flow/NPV models we identify for each project a "twin security" with the same risk characteristics which is traded in financial markets, and use its equilibrium expected rate of return as the appropriate discount rate. (This is done typically by estimating the projects covariance with the market from the prices of a twin security and applying the Capital Asset Pricing Model.) In other words, we estimate an investment project's NPV by getting a discount rate from a traded security or traded financial assets that are assumed to have equivalent risk (most, commonly we use the weighted average cost of capital, or hurdle rate , for the organization). In similar fashion, we can value investments as real options if we can find traded financial options with similar risk characteristics, or if we can identify the characteristics of the real option that are relevant for option-pricing models, including variability of potential returns (volatility), time till expiration, risk-free rates, exercise prices, and investment costs.

The analogy between real options and call options on stocks is close but not exact.[14] A standard call option on a stock is "proprietary" in that it gives the holder an exclusive right to exercise and to thus receive the benefits. Some investment opportunities are similar in that they are proprietary in providing their holder with exclusive rights of exercise - such as patents,

[13] See the references at the end of this paper for full citations; each of these approaches in developed in a number of academic papers.
[14] This typology is presented by L. Trigeorgis, "Real Options and Interactions with Financial Flexibility," *Financial Management*, Vol. 22 No. 3, Autumn 1993, pp. 202-224.

licenses, and unique know-how of a technology. Other types of investment opportunities, however, may be jointly held by more than one organization. These real options are “shared” in that, as collective opportunities of the industry, they can be exercised by any one of the participants. The distinction between shared and proprietary options may not be so clear-cut in practice. For example, if one of the collective owners of a shared option faces lower investment or implementation costs than the others (perhaps due to more pending capital investment requirements), the shared option might be treated effectively as proprietary, or at least as having competitive effects in an industry.

Another difference is that standard call options on stocks are “simple” in that their value derives entirely from the received shares. Similarly, some real options are simple in that their value depends upon the value of the underlying project. Other real options, however, may lead to further discretionary investment opportunities when exercised. In essence, they are options on options, or “compound options” (that is, an option whose payoff is another option). An investment in R&D is undertaken not just for the sake of the underlying asset but also for the new opportunities that may be opened up (a new technological breakthrough, cost reduction, etc.). These compound real options should be looked at not as independent investments but rather as links in a chain of interrelated projects, the earlier ones of which are prerequisites for later ones.

Financial options theory can be applied to real options with a few adjustments. The quantitative origins of real options derive from the seminal work of Black and Scholes and Merton (1973) in pricing financial options. Cox, Ross, and Rubinstein’s (1979) binomial approach to options enabled a more simplified valuation of options in discrete time. Geske (1979) values a compound option (i.e., an option to acquire another option), which in principle may be applied in valuing growth opportunities that become available only if earlier investments are undertaken. This line of work has the potential to value investments with a series of investment outlays that can be switched to alternative states of operation (e.g., from basic to applied research to development of prototypes), and particularly to eventually help value strategic interproject dependencies.

More generally, Constantinides (1978), Cox, Ingersoll, and Ross (1985), and Harrison and Kreps (1979), have suggested that any contingent claim on an asset, traded or not, can be priced in a world with systematic risk by replacing its expected cash flow or actual growth rate with a certainty equivalent growth rate (by subtracting a risk premium appropriate in market equilibrium) and then behaving as if the world were risk-neutral. This is analogous to discounting certainty-equivalent cash flows at the risk-free rate, rather than expected cash flows at the risk-adjusted rate. For traded assets in equilibrium or for real assets with no systematic risk (e.g., research and development), the certainty-equivalent or risk-neutral growth rate just equals the risk-free rate. Thus, we can approach R&D investment as an application of contingent claims analysis, a particular class of options.

In the wake of these theoretical developments, a variety of papers were published which focused on valuing quantitatively - in many cases deriving analytic, closed-form solutions- a variety of real options. Growth options (as exemplified by R&D projects) were discussed by

Myers (1987), Brealey and Myers(1991), Kester (1984,1993), Trigeorgis and Mason (1987), Trigeorgis (1988), and Pindyck (1988). Trigeorgis and Kasanen (1991) examine sequential project interdependencies and synergies as part of an ongoing process of planning an budgetary control. Kasanen (1993) and Kemna (1993) also deal with the strategic problem of the interaction between current investments and future opportunities, using a spawning matrix to determine the optimal mix of strategic and operating projects.

In more complex real-life situations, such as those involving interacting real options, analytic solutions may not exist and one may not even be able to write down the underlying stochastic processes. The ability to value such complex option situations has been enhanced, however, by various numerical analysis techniques, many of which take advantage of risk-neutral valuation. Generally there are two types of numerical techniques for option valuation: those that approximate the underlying stochastic processes directly (and which are generally more intuitive), and those that approximate the resulting partial differential equations form the stochastic processes. The first category included Monte Carlo simulation and various lattice approaches. Lattice approaches, such as Cox, Ross and Rubinstein (1979) and Trigeorgis (1991b), while less intuitive, are particularly well-suited to valuing complex projects with multiple embedded real options, as series of investment outlays, and option interactions. Examples of the second category (differential equations approximation) include numerical integration and finite-difference schemes, as discussed by Brennan (1979), Brennan and Schwartz (1977,1978), and Majd and Pindyck (1987). For a comprehensive review of numerical techniques, see Geske and Shastri (1985) and Hull (1993).

Using Real Options Approaches in Capital Budgeting

The basic inadequacy of the NPV approach and other Discounted Cash Flow approaches to capital budgeting is that they ignore the underlying stochastic return characteristics of research and development activities and that they ignore management's flexibility to adapt and revise later decisions. Management's flexibility to adapt its future actions depending on the future environment introduces an asymmetry or skewness in the probability distribution of NPV that expands the investment opportunity's true value by improving its upside potential while limiting downside losses relative to initial, naive expectations. In the absence of such managerial flexibility, the probability distribution of NPV would be reasonably symmetric, in which case the static expected NPV would be its most likely estimate. When managerial flexibility is present, though, (such as the option to continue, expand, or defer a project), this provides a better adaptation to future events turning out differently than what management expected at the outset. this introduces a truncation with enhanced upside potential so that the resulting actual distribution is skewed to the right (that is, more valuable). The true expected value of such an asymmetric distribution (which is referred to as the expanded NPV- "expanded" in the sense that it incorporates managerial operating flexibility and strategic adaptability) exceeds the expected value of the mean of the symmetric distribution by an option premium, reflecting the value of managerial flexibility.

This asymmetry introduced by managerial flexibility calls for an expanded NPV criterion that reflects both components of an investment opportunity's value: the traditional static NPV of directly measurable cash flows and an option premium capturing the value of strategic and operating options under active management. The motivation for using such an options-based approach to capital budgeting arises from its potential to conceptualize and quantify the flexible/sequential component of value. This does not mean that traditional NPV calculations should be rejected, but rather that they need to be augmented by option aspects in an expanded NPV framework.

Investment Opportunities as Collections of Real Options

The operating flexibility and strategic value of many research and development projects cannot be properly captured by traditional Discounted Cash Flow techniques, because of their discretionary nature, the asymmetric structure of stochastic returns, and their dependence on future events that are uncertain at the time of the initial decision. nevertheless, we can analyze these important aspects by thinking of investment opportunities as collections of options on real assets through the options-based techniques of contingent claims analysis. Just as the owner of an American call option on a financial asset has the right - but not the requirement - to acquire the asset by paying a predetermined price (the exercise price) on or before a predetermined date (the exercise or maturity date), and will exercise the option if it has value, so will the holder of an option on real assets. The owner of a discretionary investment opportunity has the right - but not the obligation- to acquire the present value of expected cash flows by making an investment outlay on or before the anticipated date when the investment opportunity will cease to exist. As shown in Exhibit 3 there exists a close analogy between such real investment opportunities and call options on stocks.

Exhibit 3
Comparisons between Financial and Real Options

Call Option on Stock	**Real Option on Project**
Current value of stock	(Gross) PV of expected cash flows
Exercise price	Investment cost
Time till expiration	Time till opportunity disappears
Stock value uncertainty	Project value uncertainty
Riskless interest rate	Riskless interest rate

Source: L. Trigeorgis, *Real Options: Managerial Flexibility and Strategy in Resource Allocation*, (Cambridge: MIT Press, forthcoming, 1996).

Even if no other associated real options exist, the flexibility to defer or expand future R&D after receiving additional information has a positive value even if immediately undertaking the project has a negative static NPV. Such flexibility gives management the right to wait until more information arrives and make the subsequent investment in the R&D program only if the value of the project turns out to exceed the necessary outlay, without imposing the symmetric obligation to invest and incur losses if the initial stage R&D is not successful.

Most of the important payoffs of managerial flexibility can be captured in a simplified way by combining these simple options in a series of sequential building blocks.

Developing a New Project Evaluation Method Using Options

In practice, organizations often classify projects according to stage of development or risk level or functional characteristics (e.g., replacement or new product introduction). This is intended to group projects of similar life, type, and risk and thus simplify the process of capital budgeting an choice across projects. These schemes are incomplete, however, in that they often overlook the options aspects of projects. To see this, let us start with a simple NPV example and develop the options framework, highlighting one aspect at a time. [15]

Traditional NPV analysis generally ignores strategic games, it also is further limited in that it assumes that management is passive -- that is, all decisions are taken up front, as if management does not have the flexibility to review and revise its original plans in light of new developments, information, or opportunities. In the absence of such managerial flexibility, static or passive NPV would be correct: management allocates funds only if the present value of expected inflows (V) is greater than the present value of investment outlays (I); in equation terms, if $NPV = V - I > 0$.[16]

But what is really of interest is not the value of the *immediate* investment per se, but rather the value of the investment *opportunity.* In a world of uncertainty, where the value of research may fluctuate and may even be unknown going in, the opportunity to invest may be more valuable than the initial investment, since it allows management the flexibility to defer undertaking the investment until circumstances turn more favorable, or to back out altogether if the project doesn't work out. On the upside, the flexibility gives management the opportunity to scale up or accelerate a successful research effort. From the Black-Scholes option-pricing formula

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[15] This framework follows that of L. Trigeorgis, *Real Options: Managerial Flexibility and Strategy in Resource Allocation*, (Cambridge: MIT Press, forthcoming, 1996).

[16] Note that the ability to delay an investment does not necessarily confer flexibility upon it. If the investment requires commitment, for example, a need to meet environmental regulations two years hence, the project still can be evaluated in static NPV terms; it is equivalent to a forward contract on an investment, appropriately discounted.

(adjusted for a cash dividend payout δ, a return shortfall to account for the nontraded character of the real option[17]), this value may be expressed as

$$C(V,t,I) = Ve^{-\delta t} N(d_1) - Ie^{-rt} N(d_2)$$

The value of this opportunity to invest therefore exceeds the static NPV of cash flows from immediate investment (V-I) by the value of the flexibility to defer, expand, or abandon the investment in the future. Such an investment opportunity may thus be economically desirable even if the investment itself has a negative NPV (i.e., V<I).

A second class of investment that involve managerial flexibility for which options approaches are relevant are multi-stage projects. Consider a research project that is not a single one-time commitment but rather a sequence of investment "installments", starting immediately and extending throughout much of the life of the investment. If managerial flexibility is introduced, this type of project highlights a series of distinct points in time -- decision nodes - when the project might be better discontinued, or where it might be applied to new areas. Discounted Cash Flow techniques, especially NPV, that deal with a sequence of investment installments simply by subtracting their present value from the value of the expected cash inflows clearly undervalue such investments.

With such contingent or interdependent projects, undertaking the first project is a prerequisite for the next or where the first project provides the opportunity to acquire at maturity the benefits of the new investment by making a new outlay. For example, a research project, if successful, provides at completion the opportunity to acquire the revenues of the developed, commercialized product upon incurring a production outlay. This idea of interproject compoundness is remarkably similar in structure to the intraproject compoundness described above, with the difference that each investment installment now provides the opportunity to begin a new project rather than continue another phase of the same one. These types of compound options are shown in Exhibit 4. Compoundness between projects is an interaction of considerable strategic importance, since it may justify the undertaking of projects with a negative NPV for direct cash flows because the project creates subsequent future investment opportunities, growth options, or organizational competencies.

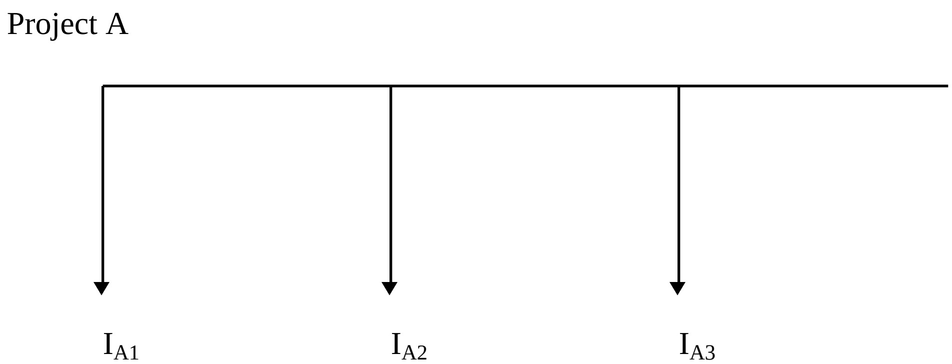
In total, the structure of options applications in capital budgeting might be described as an "expanded NPV" criterion which is defined by Trigeorgis (1993,1996) as

Expanded NPV = Direct (passive) NPV + Strategic Value + Flexibility Value

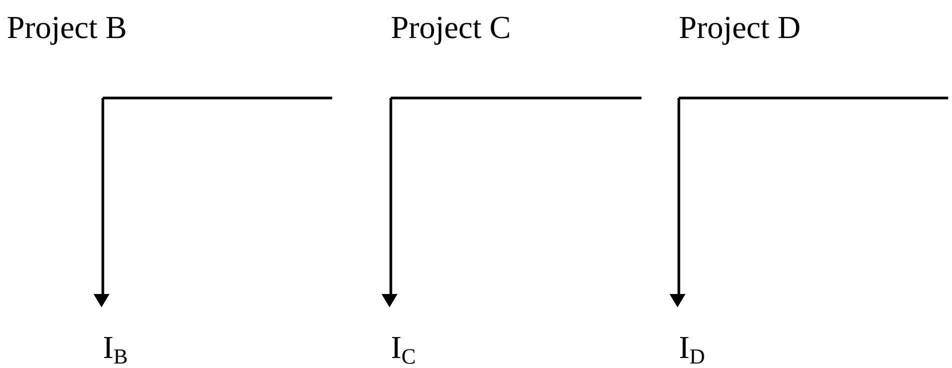
In general, the strategic value may be positive (if early investment creates a proprietary cost or performance advantage or if it deters competitive entry or response) or it may be negative (if early investment "proves" the market so that others do not have to undertake such research or

[17] This adjustment is included because the nontraded character of the real option reduces the liquidity of the investment by some amount, here noted as δ.

if the research creates shared benefits that competitors may exploit more fully than the investing firm.). For NASA, this strategic aspect is likely to be positive in most cases, because NASA may undertake research activities that may have industry wide benefits but that would not be undertaken by individual firms because the benefits could not be limited to the company. While this is unlikely to be true for safety research, for example, it does characterize may performance enhancing or cost reducing R&D efforts. Thus early investments in pioneering projects are seen to have two main effects on value: a commitment effect (which influences the form's competitive position and cash-generating ability in a later stage of the market) and a flexibility effect (which captures the firm's ability to alter its future contingent investment decisions under sequential resolution of uncertainty). For NASA, both options-aspects are of considerable importance: strategic aspects influence NASA's ongoing research capabilities, while the flexible aspects impact on NASA's ability to make sound budgetary decisions on R&D activities over time.



Intraproject compoundness (a single project A with many investment-cost installments)



Interproject compoundness (a sequence of many single-outlay interdependent projects)

Exhibit 4: Types of Compound Options

This set of perspectives might be summarized in Exhibits 5 and 6. The first shows the set of strategic questions for capital budgeting analysis. The key aspects are the proprietary or shared nature of the research (P versus S); the simple or compound nature of the option (S versus C); and the urgency in the sense of importance of an expiring or deferrable opportunity (E versus D). This conceptual framework leads us to a classification scheme shown in Exhibit 6. Although the distinctions between the various categories may at times be relative rather than absolute, most real investment opportunities, including strategic ones, can find a place on one of the eight branches of the options-based classification tree. For NASA, most research projects we might expect to fall either in the category Proprietary-Compound-Deferrable (if the applied development is undertaken through license or with a specific partner) or Shared-Compound-

Deferrable (if the research has a general industry or societal audience, such as dissemination of new testing techniques, etc.).

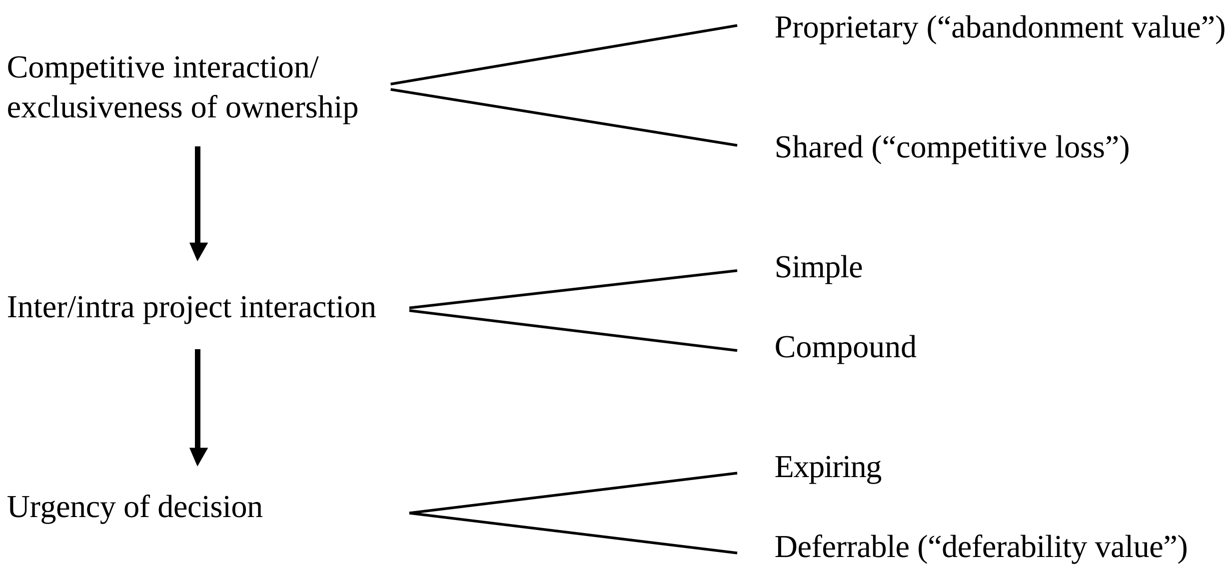


Exhibit 5: Strategic questions in capital budgeting

- Real Options
  - Proprietary
    - Simple
      - Expiring — P-S-E — Routine Maintenance
      - Deferrable — P-S-D — Plant Modernization
    - Compound
      - Expiring — P-C-E — Immediate Franchise Offer
      - Deferrable — P-C-D — R&D of a unique product
  - Shared
    - Simple
      - Expiring — S-S-E — Bidding for purchase of a firm’s assets
      - Deferrable — S-S-D — New product introduction (close substitutes)
    - Compound
      - Expiring — S-C-E — Bidding for acquisition of an unrelated company
      - Deferrable — S-C-D — Opportunity to enter a new geographic market

Exhibit 6: Classifying Types of Real Options

Source: L. Trigeorgis, *Real Options: Managerial Flexibility and Strategy in Resource Allocation*, (Cambridge: MIT Press, forthcoming, 1996).

Applying the Model to R&D Projects

Example One: Valuing a Basic Research Venture[18]

Consider a high technology project that involves high initial costs and insufficient projected cash inflows to justify it on a static NPV basis. Suppose such a project required an investment outlay (amounts in millions)of I_0 = \$500 and expected cash inflows over the next four years of C_1 = \$100, C_2 = \$200, C_3 = \$300, and C_4 = \$100. See Exhibit 7. Management feels that the new technology might enhance the company's position, though, if a market or spin-off product should develop as a result of the initial project. Even if the pioneer venture itself does not appear profitable, valuable expertise and opportunities in other areas may be lost. Investing in the pioneer venture derives strategic value from the generation of growth opportunities to invest in future commercial projects. If the technology is proven, commercial value may be many times the size of the pioneer venture. Suppose such a commercial venture, were it to occur, would become available in year 4 and be three times the size of the pioneer venture, both in terms of initial investment required and in terms of expected project cash flows over the subsequent 4 years (in this example, from years 5-8.

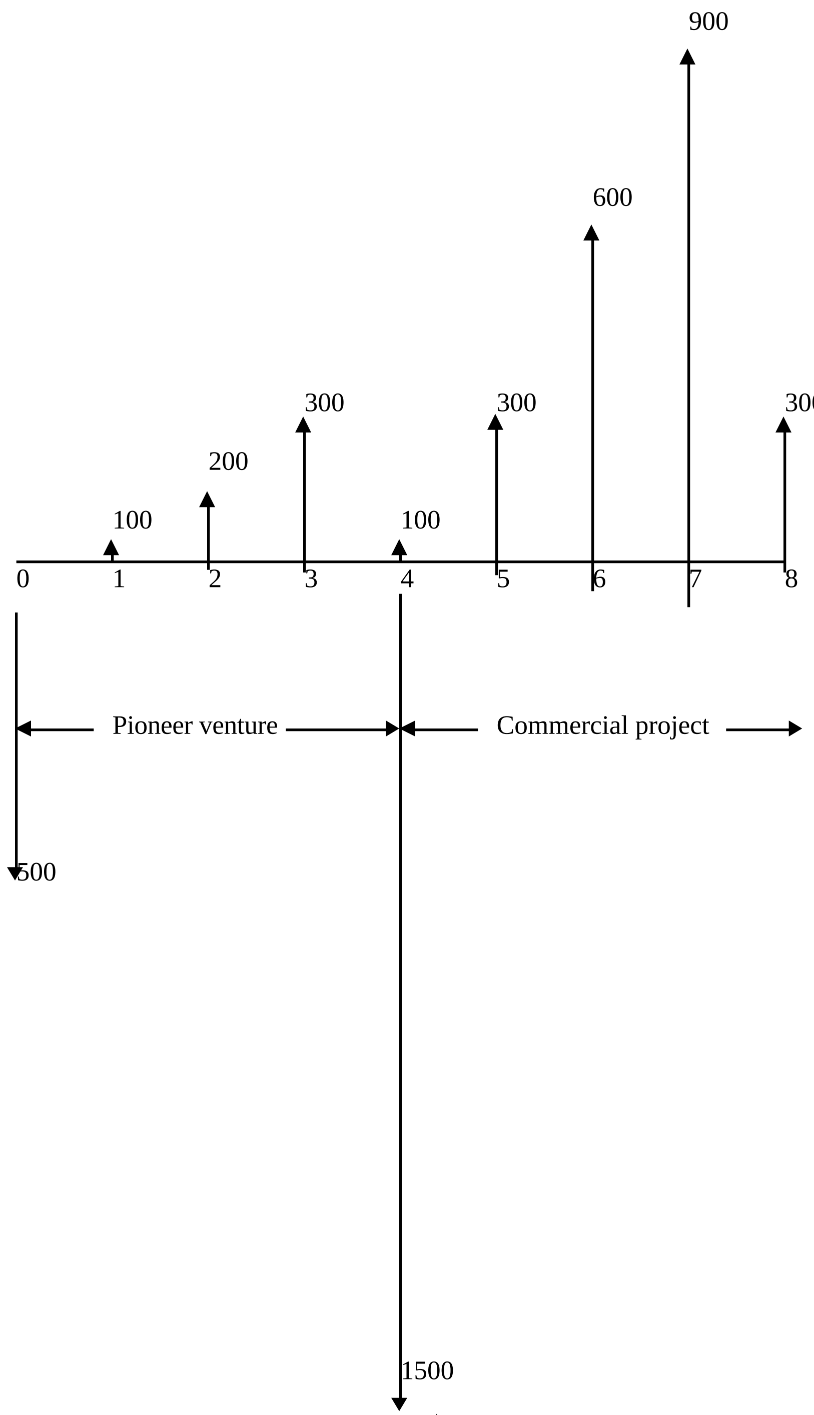
The present value (static NPV) of the expected inflows expected from the pioneer venture, discounted at an opportunity cost of capital of 20%, is V_0 = \$444 million. Thus, the static NPV is V_0 - I_0 = 444 - 500 = -\$56 million. The expected cash flows therefore make the venture unattractive by itself. The follow-up commercial project does not look any better. It requires an outlay of I_4 = \$1.5 billion, only to generate a discounted value of subsequent cash inflows at that time of V_4 = \$1.332 billion. Its NPV as of year 4 is -\$168 million (which is also three times the negative NPV of the pioneer venture). If this follow-on project is discounted back to time zero, the commitment to the commercial project has a NPV of - \$56 million (= -\$168 million discounted 4 years at 20%). Thus if the entire sequence were evaluated as of time zero, the net value would amount to -\$56 million + -\$81 million = -\$127 million.

However, management realizes that it will invest in the commercial project in year 4 only if the market is proven by that time and if the project appears profitable. Thus, investing in the negative-NPV pioneer project is like incurring a cost to buy the option, giving the firm the right (but not the obligation) to acquire the benefits of the startup venture. The option will be exercised only if the then (year 4) value of subsequent cash flows is sufficiently high. The -\$56 million NPV of the pioneer venture is the price that must be paid to acquire the growth option in the commercial project. The more uncertain the technology or the future market opportunity, the higher the value of the option to "wait and see". The question is, is the value of this option worth that cost?

To check, we can see that the growth option represented by the right to invest in the commercial venture is like a European call option with time to maturity t = 4 years and exercise

[18] The authors would like to thank Lenos Trigeorgis for providing us with the structure for this illustration.

price E = $1.5 billion. The underlying asset value is the current (time t = 0) value of a claim on the commercial project's expected future cash inflows. This can be obtained by discounting the



Capital outlays (↓) and expected cash inflows (↑) for the pioneer venture to prove a new technology, and potential follow-on commercial project to be acquired if the market develops.

Exhibit 7: Cash Flows for Basic Research Venture

time T = 4 value of the cash inflows ($1.332 billion) back to the present at the 20% discount rate (k = .20). That is,

$V_0 = V_4 e^{-kt} = \$1.332\ e^{(-.20*4)} = \$598.5$ million

Since the technology to be tested is quite uncertain, suppose we can represent the risk in outcome with a standard deviation of $\sigma = 0.35$. Also, suppose we assume that the risk-free rate is 10%. Given this information, we can obtain the Black-Scholes option value by noting that

$$\sigma\sqrt{t} = 035\sqrt{4} = 07$$

and

$$\frac{V_0}{Ee^{-rt}} = \frac{5985}{1500 * e^{-(.40)}} = 06$$

From standard options tables, we can find that the value of the call option relative to asset price given the above values of (price divided by the PV of exercise price) and (product of the standard deviation and the square root of time) is 0.1185, or 11.85% of V_0. Thus, the value of the growth option to acquire the commercial project in year 4 if the pioneer venture pans out is currently worth 0.1185 * $598.5 = $71 million. Therefore, the total strategic or expanded NPV of the pioneer project is -$56 + 71 = $15 million. Management's intuition that it should consider the pioneer venture for the new technology opportunity is justified in this case, despite the negative NPV of its own direct cash flows.

Example 2: Use of Options Analysis for R&D Projects at Merck[19]

In research and development, many high-technology companies invest heavily in technologies that may result in a wide range of possible outcomes and new potential markets, but with a high probability of technical or market failure. Such investments are hard to sell to top management on financial grounds; their benefits are remote and hard to quantify, even though intuitively their growth potential seems promising. Instead of ignoring these opportunities , a firm can make a capital commitment in stages, effectively taking a call option on the underlying technology or on future applications. The initial outlay is not made so much for its own cash flows as for its growth option value. Such is the case with almost all basic research.

Pharmaceutical companies often enter into collaborative agreements with smaller biotechnology companies in order to gain access to early-stage research projects. Because of the

[19] This section is drawn from N. A. Nichols, "Scientific Management at Merck: An Interview with CFO Judy Lewent," *Harvard Business Review*, January-February 1994, pp. 88-99.

small chance of making it to market, to control risk and preserve abandonment options, financing by the large firm is often staged as a series of contingent progress installments, with an early payment (akin to an option premium) giving the right to make future investments in clinical trials or commercialization, if warranted.

The Financial Evaluation and Analysis Group at Merck uses options approaches to evaluate R&D opportunities. One such proposal was called Project Gamma. Merck wanted to enter a new line of business that required technologies developed by a small biotech company code-named Gamma. The technologies would need to be transferred from basic to applied stage of research; scale up of manufacturing would be required, with uncertain technical feasibility; regulatory aspects needed to be resolved; and products would eventually need to be commercialized.

Under the terms of the proposed agreement, Merck would make a $2 million payment to Gamma over a three year period. In addition, Merck would pay royalties to Gamma if the product ever came to market. Merck had the option to terminate the agreement at any time if dissatisfied with the progress of the research. In short, the project had all the characteristics of a real option ,and also, due to time, uncertainty , and asymmetry in returns, was not the type of project that should be evaluated using traditional Discounted Cash Flow/NPV methods.

Two factors determine the project's option value. The first is the length of time the project might be deferred. (The longer Merck had to examine future developments, the more information it might have to make a better investment decision. the second key factor was the high degree of uncertainty (project volatility). In this case, the project's value is increased because the project structure limited Merck's downside loss to the initial $2 million, while substantial upside potential existed if things turned out well.

Merck's finance group used the Black-Scholes model to determine the project's option value. The group defined the inputs as follows:

- The exercise price was defined as the capital investment to be made two years hence.
- The stock price (or value of the underlying asset) was defined as the present value of the cash flows of the project excluding the initial investment.
- The time till expiration was varied over two, three, and four years. The option was structured to be exercised in two years at the earliest; Merck thought that four years was the maximum life because they expected other companies to have similar products by then.
- The project volatility was measured using a sample of biotechnology stocks and calculating their return volatility (standard deviation). A conservative range for the volatility of the project was set at 40% to 60%.
- A risk-free rate of interest of 4.5% was assumed, representing the U.S. Treasury note rate over the two to four year period considered for the project.

The Financial Analysis Group at Merck declined to provide actual values for confidentiality reasons, but did note that the option provided significantly more value than the up-front payment suggested when evaluated on an NPV basis.

Merck has developed (but not made available for public use) a Research Planning Model that relies on Monte Carlo simulation to generate inputs for option analysis of R&D proposals. The model's inputs include scientific and therapeutic variables, capital expenditures, production and selling costs, product prices and quantities, and macroeconomic variables such as inflation, interest rates, and exchange rates. For each variable the model uses a range of values drawn from an assumed underlying probability distribution, generally classified as "optimistic," "expected," and "pessimistic."

The computer repeatedly draws values from permissible ranges and computes outcomes based on specified relationships (model equations). In this way, the model synthesizes probability distributions for key variables. The output from the model is not merely a point forecast for say, net present value, but a frequency distribution showing the probability that a project's NPV will exceed a certain level. When the model is run over a large number of iterations, statistics can be generated about project volatility, etc., that can then be used in option analyses. This research planning model and the accompanying commitment to options analysis is widely acknowledged to represent best current practice in R&D evaluation. Begun in 1984, within five years the Research Planning Model has been used to evaluate every significant research and development program at Merck over a twenty-year horizon.

Conclusions

Real options approaches provide a distinctive and valuable approach to evaluate investment opportunities. They are particularly important in those projects which are sequential in nature; in which uncertainty is resolved over time; where returns are not normally distributed or are asymmetric in character; and when they contain important interdependencies with future investment or other projects. All of these aspects would seem to characterize aeronautical R&D programs at NASA. As such, we feel that real options approaches offer a new and important opportunity for NASA to create investment opportunities in the future. As noted by Dixit and Pindyck,

> "...uncertainty requires that managers become much more sophisticated in the ways they assess and account for risk... The bottom line for managers is that learning how to apply the net present value rule is not sufficient. More readily than conventional calculations suggest, managers should make decisions that increase flexibility. It's important for managers to get a better understanding of the options that their companies have or that they are able to create. Ultimately, options create flexibility, and in an uncertain world, the ability to value and use flexibility is essential."[20]

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Appendix: Example of Option Value Table Entries

APPENDIX TABLE 6
Call option values, percent of share price

SHARE PRICE DIVIDED BY PV (EXERCISE PRICE)

STANDARD DEVIATION TIMES SQUARE ROOT OF TIME	.40	.45	.50	.55	.60	.65	.70	.75	.80	.82	.84	.86	.88	.90	.92	.94	.96	.98	1.00	1.02
.05	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.3	.8	1.2	2.0	3.1
.10	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.2	.3	.5	.8	1.2	1.7	2.3	3.1	4.0	5.0
.15	.0	.0	.0	.0	.0	.0	.1	.2	.5	.7	1.0	1.3	1.7	2.2	2.8	3.5	4.2	5.1	6.0	7.0
.20	.0	.0	.0	.0	.0	.1	.4	.8	1.5	1.9	2.3	2.8	3.4	4.0	4.7	5.4	6.2	7.1	8.0	8.9
.25	.0	.0	.0	.1	.2	.5	1.0	1.8	2.8	3.3	3.8	4.4	5.2	5.9	6.6	7.4	8.2	9.1	9.9	10.9
.30	.0	.1	.1	.3	.7	1.2	2.0	3.1	4.4	5.0	5.7	6.3	7.0	7.8	8.6	9.4	10.2	11.1	11.9	12.8
.35	.1	.2	.4	.8	1.4	2.3	3.3	4.6	6.2	6.8	7.5	8.2	9.0	9.8	10.6	11.4	12.2	13.0	13.9	14.8
.40	.2	.5	.9	1.6	2.4	3.5	4.8	6.3	8.0	8.7	9.4	10.2	11.0	11.7	12.5	13.4	14.2	15.0	15.9	16.7
.45	.5	1.0	1.7	2.6	3.7	5.0	6.5	8.1	9.9	10.6	11.4	12.2	12.9	13.7	14.5	15.3	16.2	17.0	17.8	18.6
.50	1.0	1.7	2.6	3.7	5.1	6.6	8.2	10.0	11.8	12.6	13.4	14.2	14.9	15.7	16.5	17.3	18.1	18.9	19.7	20.5
.55	1.7	2.6	3.8	5.1	6.6	8.3	10.0	11.9	13.8	14.6	15.4	16.1	16.9	17.7	18.5	19.3	20.1	20.9	21.7	22.4
.60	2.5	3.7	5.1	6.6	8.3	10.1	11.9	13.8	15.8	16.6	17.4	18.1	18.9	19.7	20.5	21.3	22.0	22.8	23.6	24.3
.65	3.6	4.9	6.5	8.2	10.0	11.9	13.8	15.8	17.8	18.6	19.3	20.1	20.9	21.7	22.5	23.2	24.0	24.7	25.5	26.2
.70	4.7	6.3	8.1	9.9	11.9	13.8	15.8	17.8	19.8	20.6	21.3	22.1	22.9	23.6	24.4	25.2	25.9	26.6	27.4	28.1
.75	6.1	7.9	9.8	11.7	13.7	15.8	17.8	19.8	21.8	22.5	23.3	24.1	24.8	25.6	26.3	27.1	27.8	28.5	29.2	29.9
.80	7.5	9.5	11.5	13.6	15.7	17.7	19.8	21.8	23.7	24.5	25.3	26.0	26.8	27.5	28.3	29.0	29.7	30.4	31.1	31.8
.85	9.1	11.2	13.3	15.5	17.6	19.7	21.8	23.8	25.7	26.5	27.2	28.0	28.7	29.4	30.2	30.9	31.6	32.2	32.9	33.6
.90	10.7	13.0	15.2	17.4	19.6	21.7	23.8	25.8	27.7	28.4	29.2	29.9	30.6	31.3	32.0	32.7	33.4	34.1	34.7	35.
.95	12.5	14.8	17.1	19.4	21.6	23.7	25.8	27.7	29.6	30.4	31.1	31.8	32.5	33.2	33.9	34.6	35.2	35.9	36.5	37.
1.00	14.3	16.7	19.1	21.4	23.6	25.7	27.7	29.7	31.6	32.3	33.0	33.7	34.4	35.1	35.7	36.4	37.0	37.7	38.3	38.
1.05	16.1	18.6	21.0	23.3	25.6	27.7	29.7	31.6	33.5	34.2	34.9	35.6	36.2	36.9	37.6	38.2	38.8	39.4	40.0	40.
1.10	18.0	20.6	23.0	25.3	27.5	29.6	31.6	33.5	35.4	36.1	36.7	37.4	38.1	38.7	39.3	40.0	40.6	41.2	41.8	
1.15	20.0	22.5	25.0	27.3	29.5	31.6	33.6	35.4	37.2	37.9	38.6	39.2	39.9	40.5	41.1	41.7	42.3	42.9	43.5	
1.20	21.9	24.5	27.0	29.3	31.5	33.6	35.5	37.3	39.1	39.7	40.4	41.0	41.7	42.3	42.9	43.5	44.0	44.6	45.1	45.
1.25	23.9	26.5	29.0	31.3	33.5	35.5	37.4	39.2	40.9	41.5	42.2	42.8	43.4	44.0	44.6	45.2	45.7	46.3	46.8	47.
1.30	25.9	28.5	31.0	33.3	35.4	37.4	39.3	41.0	42.7	43.3	43.9	44.5	45.1	45.7	46.3	46.8	47.4	47.9	48.4	48.
1.35	27.9	30.5	33.0	35.2	37.3	39.3	41.1	42.8	44.4	45.1	45.7	46.2	46.8	47.4	47.9	48.5	49.0	49.5	50.0	50.
1.40	29.9	32.5	34.9	37.1	39.2	41.1	42.9	44.6	46.2	46.8	47.4	47.9	48.5	49.0	49.6	50.1	50.6	51.1	51.6	52.
1.45	31.9	34.5	36.9	39.1	41.1	43.0	44.7	46.4	47.9	48.5	49.0	49.6	50.1	50.7	51.2	51.7	52.2	52.7	53.2	53.
1.50	33.8	36.4	38.8	40.9	42.9	44.8	46.5	48.1	49.6	50.1	50.7	51.2	51.8	52.3	52.8	53.3	53.7	54.2	54.7	55
1.55	35.8	38.4	40.7	42.8	44.8	46.6	48.2	49.8	51.2	51.8	52.3	52.8	53.3	53.8	54.3	54.8	55.3	55.7	56.2	56
1.60	37.8	40.3	42.6	44.6	46.5	48.3	49.9	51.4	52.8	53.4	53.9	54.4	54.9	55.4	55.9	56.3	56.8	57.2	57.6	58
1.65	39.7	42.2	44.4	46.4	48.3	50.0	51.6	53.0	54.4	54.9	55.4	55.9	56.4	56.9	57.3	57.8	58.2	58.6	59.1	59
1.70	41.6	44.0	46.2	48.2	50.0	51.7	53.2	54.6	55.9	56.5	57.0	57.4	57.9	58.4	58.8	59.2	59.7	60.1	60.5	60
1.75	43.5	45.9	48.0	50.0	51.7	53.4	54.8	56.2	57.5	58.0	58.5	58.9	59.4	59.8	60.2	60.7	61.1	61.5	61.9	62
2.00	52.5	54.6	56.5	58.2	59.7	61.1	62.4	63.6	64.6	65.0	65.4	65.8	66.2	66.6	66.9	67.3	67.6	67.9	68.3	68
2.25	60.7	62.5	64.1	65.6	66.8	68.0	69.1	70.0	70.9	71.3	71.6	71.9	72.2	72.5	72.8	73.1	73.4	73.7	73.9	74
2.50	67.9	69.4	70.8	72.0	73.1	74.0	74.9	75.7	76.4	76.7	77.0	77.2	77.5	77.7	78.0	78.2	78.4	78.7	78.9	79
2.75	74.2	75.4	76.6	77.5	78.4	79.2	79.9	80.5	81.1	81.4	81.6	81.8	82.0	82.2	82.4	82.6	82.7	82.9	83.1	83.
3.00	79.5	80.5	81.4	82.2	82.9	83.5	84.1	84.6	85.1	85.3	85.4	85.6	85.8	85.9	86.1	86.2	86.4	86.5	86.6	86
3.50	87.6	88.3	88.8	89.3	89.7	90.1	90.5	90.8	91.1	91.2	91.3	91.4	91.5	91.6	91.6	91.7	91.8	91.9	92.0	92
4.00	92.9	93.3	93.6	93.9	94.2	94.4	94.6	94.8	94.9	95.0	95.0	95.1	95.2	95.2	95.3	95.3	95.4	95.4	95.4	95
4.50	96.2	96.4	96.6	96.7	96.9	97.0	97.1	97.2	97.3	97.3	97.3	97.4	97.4	97.4	97.5	97.5	97.5	97.5	97.6	97
5.00	98.1	98.2	98.3	98.3	98.4	98.5	98.5	98.6	98.6	98.6	98.6	98.7	98.7	98.7	98.7	98.7	98.7	98.7	98.8	9

Note: Based on Black-Scholes model. To obtain corresponding European put values, add present value of exercise price and subtract share price.